

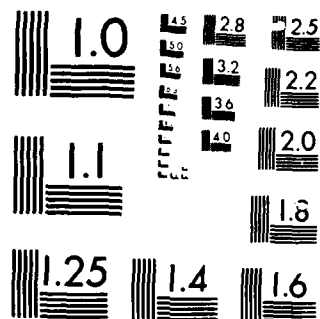
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OPTICAL FEEDBACK STABILIZATION OF LASER  
DIODES FOR PASSIVE RESONANCE RING LASER  
GYRO APPLICATIONS

THESIS

Daniel J. Stech, Captain, USAF

AFTT/GE/ENG/86D-44

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THESIS

Presented to the Faculty of the School of Engineering  
of the Air Force Institute of Technology

Air University

in Partial Fulfillment of the  
Requirements for the Degree of  
Master of Science

Daniel J. Stech  
Capt, USAF

December 1985

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## Preface

Passive ring laser gyroscopes are becoming very important to navigation systems. The days of small, accurate, reliable, and rugged optical rotation sensors are not far off. The main purpose of this research was to a construct narrow spectral linewidth semiconductor laser. In future research, this modified laser will be locked to a stable, very high finesse ring cavity. The ultimate objective is to construct a highly sensitive semiconductor laser based passive resonant ring laser gyroscope.

I would like to thank Lt Col Biezed for acting as my thesis advisor, allowing me to pursue this exciting experimental thesis research. I would like to thank Dr. J.L. Hall of JILA in Boulder for all the times he helped me get "unstuck", for interesting discussions and many electronics lessons. I would like to thank all the personnel in the gyro section of the FJSRL for all their help and support, especially Maj Shaw, Maj Rotge and Leno Pedrotti. Without all these people help I could never have finished this project in one summer.

Finally, I would like to thank my wife Bernadette for all her love, support and patience during this entire project. This thesis is dedicated to my son Joey who was born 7 weeks before its completion.

Capt. Daniel Stech

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# ABSTRACT

Reduced cost, greater reliability, and compatibility with integrated optics are some of the advantages gained by incorporating semiconductor lasers into the design of passive resonant ring laser gyroscopes (PRRLG). Unfortunately the large spectral linewidth typical of semiconductor lasers greatly limits the sensitivity of such a configuration. This research details the modification of a laser diode to obtain a stable, single mode, narrow spectral output. Optical feedback was investigated to obtain spectral narrowing of the laser diode. An optical feedback configuration compatible with the input optics to a PRRLG was designed. Spectral narrowing and modal dynamics of the external coupled cavity laser were measured. By temperature stabilization and optical feedback a free running linewidth of 60 MHz was reduced to below 13 Mhz and was maintained in a single mode for 20 minutes or more.

# OPTICAL FEEDBACK FREQUENCY STABILIZATION OF LASER DIODES FOR PASSIVE RESONANT RING LASER GYROSCOPES

## I. INTRODUCTION

The mechanical gyroscope has been a standard rotation sensor since its development for use as an inertial sensor. Years of refinement have resulted in very precise mechanical gyros exhibiting drift rates of less than  $10^{-4}$  degrees/hour. Unfortunately these instruments, when used in high precision applications are very complex to fabricate. The high and rising cost of skilled labor and precision components has made them an expensive commodity. It is ironic that the laser, a high technology item, may eventually solve the mechanical rate sensor's cost and complexity problems. The word gyroscope, coming from the greek terms meaning "to view" and "to rotate", is as applicable to laser beams as to the rotating mass which they replace.

The first working ring laser gyro (RLG) was built by Macek and Davis in 1963 (1) and has many desirable technical qualities. The RLG is virtually acceleration resistant, it requires very little warmup time, and since there are no moving parts, maintenance and mean time between failure (MTBF) are drastically reduced. The first RLG designs were considered "active" RLGs since the lasing (gain) medium was actually contained in the ring cavity.

This "active design has inherent problems, the most troublesome being an insensitivity to low rotation rates (lock-in). Lock-in results from the gain medium and light beams occupying the same cavity (2). The methods used to attack problems such as lock in, increase the complexity and cost of the active RLG. In an effort to bypass the problems associated with containing the gain medium in the ring cavity, a new class of RLGs which do not contain the gain medium in the cavity were devised. These are known as passive resonant ring laser gyroscopes (PRRLGs).

In 1977 Ezekiel and Balamo proposed the PRRLG (3). The PRRLG has a ring cavity, like the active RLG; however, an external laser injected into the cavity is used to generate the two counter propagating beams. Electronic control loops are used to keep the two beams in resonance with the cavity. PRRLGs have already demonstrated high sensitivities to low rotation rates.(4)

Another interesting feature of the PRRLG is that unlike active RLGs, semiconductor laser sources may be used. Semiconductor lasers are much smaller, cheaper, and more reliable than gas lasers. Additionally, the ability to use semiconductor laser sources and the resonator construction make the PRRLG the configuration which is best suited for implementation using integrated optics technology. Using semiconductor lasers and lithium niobate optical resonator technology, construction of an integrated optical

gyro is possible using low cost thin film technology (5). Unfortunately difficulties exist in the direct incorporation of semiconductor lasers into the design of highly sensitive PRRLGs.

Although semiconductor laser technology has improved, the spectral quality of light from semiconductor lasers is still much worse than gas lasers. The broad spectral linewidth of semiconductor lasers limits sensitivity. The problem is to reduce the frequency noise and consequently spectral linewidth of the semiconductor laser. Two methods have been used to frequency stabilize laser diodes, electronic feedback and optical feedback. Reduction of frequency noise and drift has been achieved by control of injection current and/or temperature with a Fabry Perot or atomic resonance as a reference (6,7,8). Another method of reducing frequency noise is that of optical feedback. Minute amounts of laser light reflected back into the cavity can narrow the spectral linewidth of the laser by as much as two orders of magnitude (9,10,11).

In this research, of optical feedback will be employed to construct a stable, narrow linewidth semiconductor laser source. This is a necessary first step in the research which will be required to construct a highly sensitive semiconductor laser based PRRLG.

Chapter II describes the problem with incorporating a semiconductor laser directly into the design of highly sensitive PRRLGs. It also contains theory which explains the sources of frequency noise in semiconductor lasers

and how it is reduced by optical feedback. and theory on the modal dynamics of the laser under feedback. Chapter III explains the equipment used and experimental setup. Finally, Chapter IV describes the analysis of the free running laser diodes and laser diodes under feedback.

## II. PRRLG Linewidth and Sensitivity

### Passive Resonant Ring Laser Gyroscopes (PRRLGs)

A laser external to the ring cavity is the prominent feature of a PRRLG. This removes the active medium from the cavity and consequently eliminates all the associated problems such as lock-in at low rotation rates, bias drift, and scale factor variation. The external laser configuration also allows the use of semiconductor lasers in the PRRLG design. Since its original proposal, a number of variations to the PRRLG have been designed and tested (12,13,14). A common configuration of the PRRLG is shown in Figure 1. (3) In this scheme a single laser beam is split into a clockwise (CW) and counter clockwise (CCW) beam. The CW beam is shifted by frequency  $f_1$ . A control loop adjusts the length of the cavity. Resonance of the CCW beam is maintained by adjusting the top acousto-optic modulator. The difference between  $f_1$  and  $f_2$  is proportional to rotation in the plane normal to the cavity. This is given by: (15)

$$\Delta f = (4A/\lambda P) \Omega \quad (1)$$

Where       $A$  = Area enclosed by the ring cavity ( $m^2$ )  
              $P$  = Perimeter of the ring cavity (m)  
              $\lambda$  = Wavelength of the light source (m)  
              $\Omega$  = Rotation rate (rad/sec)

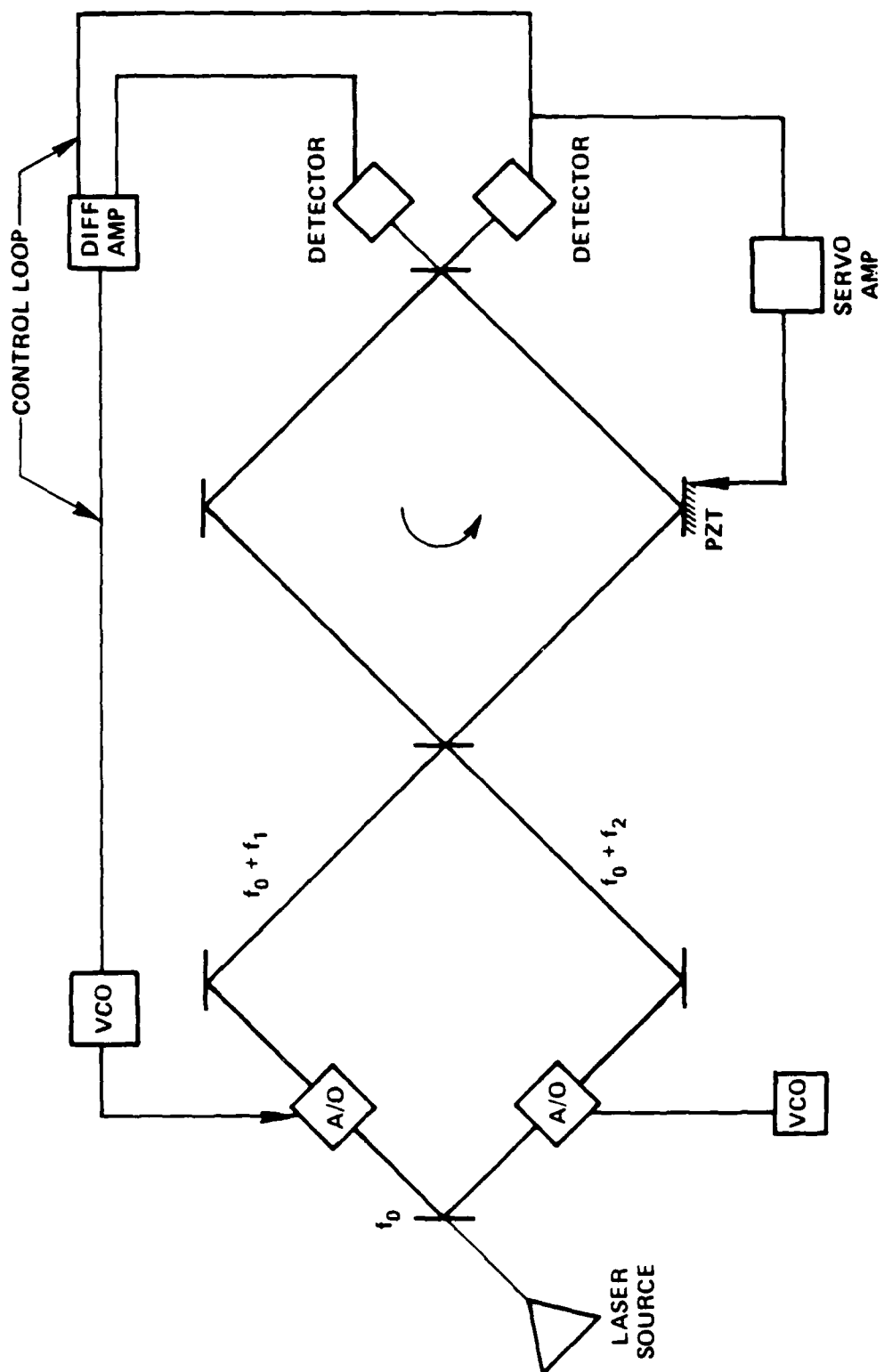


Figure 1 - PRRLG Configuration



Assuming perfect operation of the feedback loops which lock the laser to the cavity, the precision of a PRRLG is limited by the shot noise generated by the photodetectors. The maximum rotational sensitivity possible is given by: (16)

$$\delta\Omega = \frac{\lambda P}{4A} \frac{(2)^{1/2} \Gamma}{(N\eta\tau)^{1/2}} \quad (2)$$

Where  $\Gamma$  = Linewidth of the ring cavity (Hz)  
 $N$  = Number of photons/sec in the laser beam  
 $\eta$  = Quantum efficiency of the photodetector  
 $\tau$  = Averaging time (sec)  
 $\delta\Omega$  = Rotation detection limit (Hz)

The rotation detection limit should be minimized for maximum rotational sensitivity. Assuming constant photodetector parameters, reducing the cavity linewidth will reduce  $\delta\Omega$ . Narrowing the linewidth of the cavity implies improvement in the signal to noise ratio (S/N) and consequently better gyro sensitivity. The desire to keep gyro sensitivity high, however, imposes constraints on the laser source which is locked to the cavity.

Since a Fabry Perot cavity acts as an optical bandpass filter, all the light from a laser source whose spectral linewidth is greater than the bandwidth of the cavity will not be transmitted through the cavity. The narrow linewidth cavity filters out much of the power of the laser and consequently decreases the S/N. When the laser is locked to the cavity, an improvement of this condition is possible since the controller eliminates

frequency deviations from the resonant frequency of the cavity.

Unfortunately, any frequency noise which is faster than the controller (outside the bandwidth of the controller) is not effected and as a result robs power from the cavity resonant frequency; S/N is not maximized. This is the case with semiconductor lasers. Since the frequency noise is very broadband, extending out to 2 GHz (17), even very wideband controllers can only eliminate a small part of the frequency noise. As a result, it is desirable to use a wide band frequency noise reduction technique along with electronic feedback. The next section will examine sources of frequency noise in semiconductor lasers and the use of optical feedback to attain a wideband reduction in frequency noise.

#### Frequency Noise and Laser Linewidth

The ideal laser should emit light which is spectrally pure. Realistically this is not the case. In all lasers, two basic mechanisms cause laser light to deviate from single frequency operation. The first, "technical" noise, is due to mechanical effects on the laser cavity and other sources of external noise. The second mechanism is noise due to quantum fluctuations. (18)

"Technical" noise in semiconductor lasers causes fluctuations in the physical length and refractive index of the laser cavity. The frequencies at which a laser can operate are given by:

$$\nu = mc/2nl \quad m=1,2,3,\dots \quad (3)$$

Where  $\nu$  = Resonant frequency (Hz)  
 $c$  = Speed of light (m/s)  
 $n$  = Index of refraction of the cavity  
 $l$  = Length of the laser cavity (m)

$nl$  defines the optical path length. Variations in either the length or refractive index of the cavity cause variations in the optical path length and, consequently, in the operating frequencies. In semiconductor lasers, fluctuations in the length of the cavity are caused by temperature changes in the diode junction. Slow environmental temperature changes tend to result in low frequency noise or drift. Another source of "technical" noise is fluctuation in the injection current. Alternating current noise in the injection current causes the carrier density to change which results in changes in the refractive index of the cavity and thus frequency noise.

Frequency noise due to quantum fluctuations in semiconductor lasers has its origin in the spontaneous emission process. In spontaneous emission, excited atoms in the gain medium emit photons randomly resulting in instantaneous phase and intensity changes. The radiation field is coupled to the population inversion in the gain medium. The differential equations which describe this coupling show the intensity will return to a steady state value through a number of damped relaxation oscillations. (18)

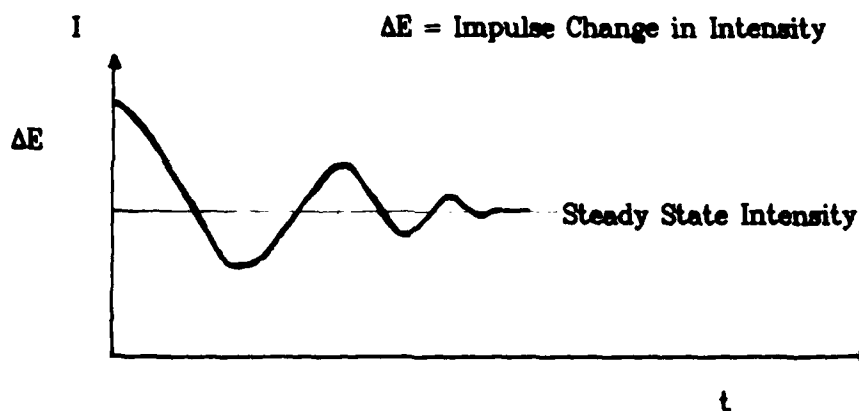


Figure 2 - Spontaneous Emission Induced Relaxation Oscillations

The phase on the other hand has no force to restore it to the original phase so it tends to drift from its original value. This phase noise introduced from spontaneous emission produces spectral broadening and gives a fundamental limit to the spectral purity of laser light. The linewidth due to spontaneous emission is given by: (18)

$$\Delta\nu = R/4\pi I \quad (4)$$

$R$  = Spontaneous emission rate (photons/sec)

$I$  = Optical intensity of the mode (photons)

In addition to the instantaneous phase change caused by spontaneous emission, there is a delayed phase change resulting from the instantaneous change in field intensity. As discussed previously, to return to steady state field intensity, the laser undergoes relaxation oscillations lasting about 1 ns. These oscillations cause a deviation in the index of refraction from its steady state value. The spectral broadening caused by

this process is the dominant source of frequency noise in semiconductor lasers (19).

Broadening of the laser spectral linewidth is due to phase fluctuations in the optical field. As examined above there are many sources of frequency noise in semiconductor lasers. This frequency noise is characterized by a large frequency noise spectrum. A typical noise spectrum for a semiconductor laser is shown:

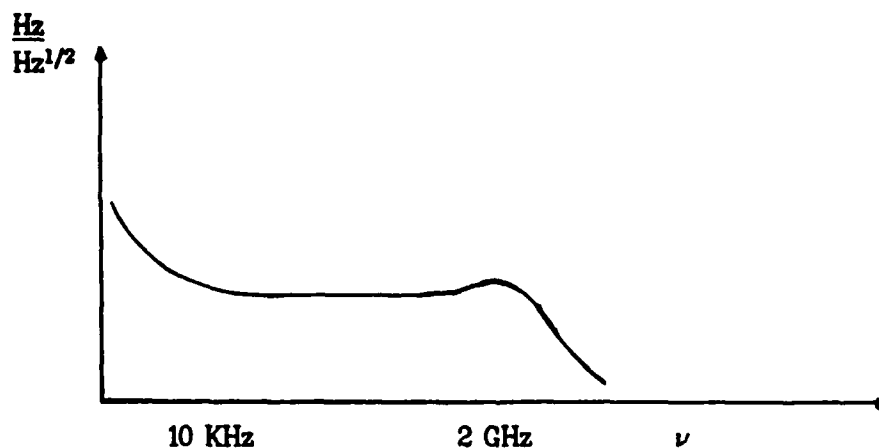


Figure 3 - Semiconductor Laser Frequency Noise PSD

The low frequency  $1/f$  component results from the "technical" noise previously discussed. The broadband frequency noise which peaks around 2 GHz corresponds to noise generated by quantum fluctuations. The peak at 2 GHz is due to a resonance at the relaxation oscillation frequency. Pure spontaneous emission contributes a nearly "white" very broadband component

to the frequency noise power spectral density. Its contribution is small compared to the effects of spontaneous emission induced refractive index fluctuations.

#### Laser Linewidth Reduction by Optical Feedback

As a result of the large frequency noise spectrum, semiconductor lasers possess a large spectral linewidth. It has been shown that a large reduction in spectral linewidth results when coupling a semiconductor laser to an external cavity. (Optical feedback) Laser linewidths as low as 100KHz have been reported (9). This section examines how optical feedback can reduce frequency noise and consequently spectral linewidth.

To review, there are three sources of frequency noise in semiconductor lasers:

1. Spontaneous emission - This causes a very wide band noise which is very small compared to the refractive index fluctuations due to spontaneous emission.
2. Refractive index fluctuation due to spontaneous emission - this causes a wideband frequency noise which peaks around 2 GHz.
3. Variations in current and junction temperature - this causes frequency drift and  $1/f$  frequency noise.

Coupling the diode laser to an external cavity will decrease frequency noise generated by spontaneous emission and frequency noise caused by relaxation oscillations of the refractive index. The reduction of frequency noise has the effect of reducing the linewidth.

Spontaneous emission. The linewidth due to spontaneous emission can be reduced by coupling the laser to an external resonant cavity. This effectively increases the Q of the overall cavity, causing a narrowing of the fundamental laser line.

The spectral linewidth due to spontaneous emission is Lorentzian in shape and is given by equation 4. Coupling the external cavity to the laser has the effect of increasing the cavity size without increasing the amount of active material. This is equivalent to increasing the total optical intensity I, without changing the spontaneous emission rate R, resulting in a linewidth reduction.

Relaxation Oscillation Frequency Noise. The optical feedback caused by an external cavity essentially decouples the frequency deviations caused by the relaxation oscillations from the laser output. The mode frequencies of a semiconductor laser are given by:

$$\nu = \frac{mc}{2l(nl)} \quad m=1,2,3,\dots \quad (3)$$

A deviation in the index of refraction  $n+\Delta n$  results in:

$$\nu = \frac{mc}{2l(n+\Delta n)} \quad (5)$$

which reduces to:

$$\frac{\Delta \nu}{\nu} = \frac{\Delta n}{n} \quad (6)$$

A fluctuation in the index of refraction is directly proportional to a

fluctuation in the frequency. An external cavity adds a length L. For a resonance to occur throughout the cavity, the length of the external cavity must be an integral multiple of the length of the laser cavity. Now the mode frequencies are given by:

$$\nu = \frac{mc}{2(nl+L)} \quad m=1,2,3,\dots \quad (7)$$

Where  $L$  = The length of the external cavity. (m)

Now a deviation in the refractive index  $n+\Delta n$  results in:

$$\nu = \frac{mc}{2[(n+\Delta n)l+L]} \quad m=1,2,3,\dots \quad (8)$$

which reduces to:

$$\frac{\Delta \nu}{\nu} = \frac{l \Delta n}{ln+L} \quad (9)$$

Since  $\Delta n$  and  $nl$  are much smaller than  $L$ , frequency fluctuation due to fluctuations of the refractive index are drastically reduced. This results in a broadband reduction in frequency noise. As expected, a reduction in the frequency noise power spectral density results in linewidth narrowing.

1/f Noise. Providing optical feedback to the semiconductor laser does not reduce 1/f or technical noise. In fact, increasing the optical length of the laser reduces the laser cavity tolerance to thermal and acoustical perturbations and tends to increase technical noise. This low frequency 1/f noise can be eliminated by electronic feedback.



### Semiconductor Laser Mode Behavior with Optical Feedback

PRRLGs require a single mode laser source, therefore, it is important to understand the effect of optical feedback on semiconductor laser mode dynamics. A semiconductor laser with proper waveguiding will operate in a single transverse and longitudinal mode. Coupling the laser to an external cavity causes quite different mode behavior. An analysis of a three mirror cavity performed by Goldberg et al (9) will help explain this mode behavior. Consider the following three mirror cavity:

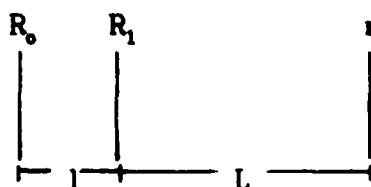


Figure 4 - Three Mirror Cavity

If  $r \ll R_1$ , then the external cavity can be viewed as a wavelength dependent perturbation of the round trip phase of the main cavity and effective reflectivity of  $R_1$ . The amplitude of the wave reflected from the facet of  $R_1$  is:

$$A = (R_1)^{1/2} + (1 - R_1)(r)^{1/2} \exp[i\theta_1] \quad (10)$$

Where  $\theta_1 = \frac{4\pi L}{\lambda}$   
 $\lambda$  = Freespace wavelength

The incident wave has amplitude one. Since  $r$  is small the main cavity phase shift is written as:

$$\theta = \theta_2 + \frac{(1-R_1)(r)^{1/2} \sin \theta_1}{(R_1)^{1/2}} \quad (11)$$

Where  $\theta_2 = \frac{4\pi n l}{\lambda}$

With no external feedback the modes of the Fabry Perot laser cavity must satisfy:

$$\theta = 2\pi l \quad l \text{ is an integer} \quad (12)$$

Now consider a single mode laser defined by integer  $l_0$  with lasing wavelength:

$$\lambda_0 = \frac{2nl}{l_0} \quad (13)$$

Small deviations of  $\lambda$  from  $\lambda_0$  give:

$$\theta = 2\pi l_0 - \frac{4\pi n l (\lambda - \lambda_0)}{\lambda^2} \quad (14)$$

This is a linear decreasing function. When feedback is added, all phase conditions must still be met, but as shown in equation 11 the phase is no longer a linear function of  $\lambda$ . If the phase verses wavelength is plotted as shown in Figure 5, the dotted line represents  $\theta$  vs  $\lambda$  for no feedback. The solid line is  $\theta$  vs  $\lambda$  in a feedback condition. For the condition in figure 5 the  $\theta$  line intersects the resonance condition  $2\pi l$  at one point, indicating a single resonance condition or mode. If feedback is increased the amplitude of the ripples on

the phase

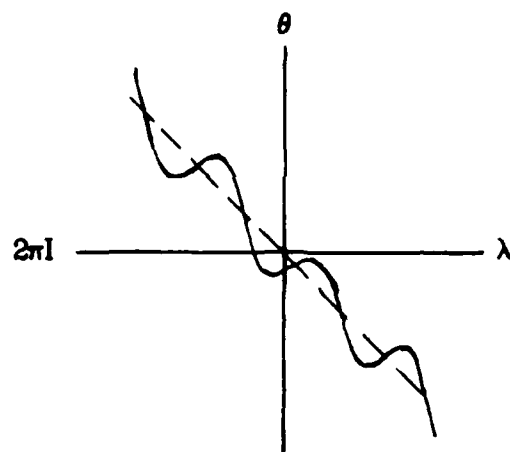


Figure 5 - Phase vs Wavelength with Moderate Feedback

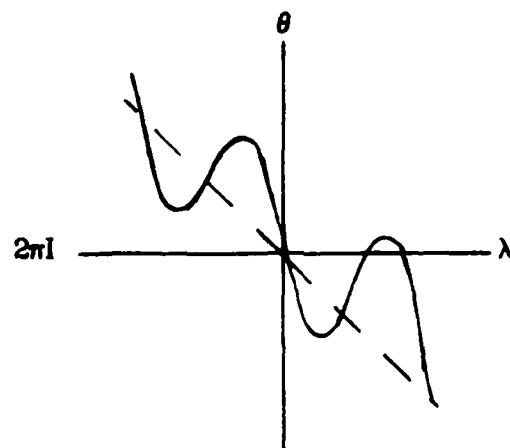


Figure 6 - Phase vs Wavelength with Strong Feedback

curve increase as shown in Figure 6. Now the plot indicates more than one resonance condition, a multimode condition. Changing the current has the effect of changing the phase of the system which translates the phase curve up and down the dotted line. This is understood as alternating between a single and multimode condition. If the amplitude of the feedback is increased still further, eventually a multimode condition will persist. Thus a limit is imposed on the amount of narrowing which can take place and still maintain a single mode.

### III. Experimental Setup

#### Equipment

Laser Diodes. Due to differences in waveguiding and manufacturing techniques, laser diodes from two different manufacturers were tested.

Mitsubishi. Two model 3101, double heterostructure AlGaAs laser diodes manufactured by Mitsubishi were used in the research. The waveguiding is transverse junction stripe which allows lasing in a single longitudinal and transverse mode. The low threshold current allows the diode mean time between failure (MTBF) to be greater than one million hours. The diodes are rated at a maximum power output of 3mW at 25 °C. The wavelength vs case temperature coefficient is given as .2nm/°C or 87 GHz/°C at 830nm. The two diodes are identified by serial as 83-15679 and 83-15492. Diode 83-15679 operates at 829nm at 24 °C, 83-15492 at 834nm at 28 °C. Two characteristics of the diodes were actually measured, power vs current and current vs frequency. The threshold currents at room temperature were 9mA and 13mA respectively. The current vs frequency coefficients were 9.2 GHz/mA for diode 83-15679 and 7.27 GHz/mA for 83-15492. Both diodes were operated at 1.5 times threshold current unless otherwise specified.

Hitachi. A diode laser, model HL 8311c manufactured by Hitachi was also tested. This was a double heterostructure AlGaAs laser

diode whose waveguiding structure is channeled planar substrate. It is structurally different than the Mitsubishi diodes but still provides a single longitudinal and transverse mode. The case and mounting system are identical to the Mitsubishi diodes. It operates at 824.6nm at 10mW at 24 °C. The threshold current was 58 mA. The frequency vs current coefficient was measured as 3.5 GHz/mA. This diode was also operated at 1.5 times threshold current.

Current Supply. A DC current supply used to power the laser diodes has two important requirements. Since the laser diode can be modulated to very high frequencies, the current supply must be free of AC noise which will generate frequency noise in the output. Secondly, the reflective facets of the laser cavity are not resistant to power surges and can easily be burned beyond usefulness with current spikes 2-3 times threshold current and as short as 1 $\mu$ s.

The power supply used to drive both brands of diodes was a Hewlett Packard 6236B. An external buffer circuit provided diode protection from transients and reverse bias voltages. (See Appendix A) The power supply with buffer circuit was checked and found to be transient free on power up and down. The current noise spectrum was checked with a Nicolet 660 spectrum analyzer. The current noise level was found to be the same or lower than the resolution limit of the spectrum analyzer. Finally long term drift was

measured with a strip chart recorder and found to be less than .012 mA over one hour.

Temperature Controller. The frequency of oscillation in a semiconductor laser is strongly dependent upon the PN junction temperature. The change in frequency vs change in temperature is device specific, however values can range as high as 90GHz/°C. To avoid large frequency drift due to ambient temperature changes the temperature of the diode must be stabilized. Since quantum efficiency and lifetime of the diode decreases as temperature increases, it is logical to control diode temperature by cooling. To control the temperature the following feedback control scheme is employed:

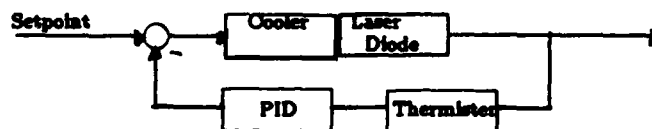


Figure 7 - Temperature Controller Block Diagram

This configuration regulates the temperature to a given setpoint by use of a proportional integral derivative controller (PID). The electronic circuit is given in detail in appendix A.

A thermister is mounted to the back side of the diode case. The diode assembly is mounted on the peltier cooler which in turn is mounted on a solid block of aluminum to act as a heat sink, as shown in the photo:

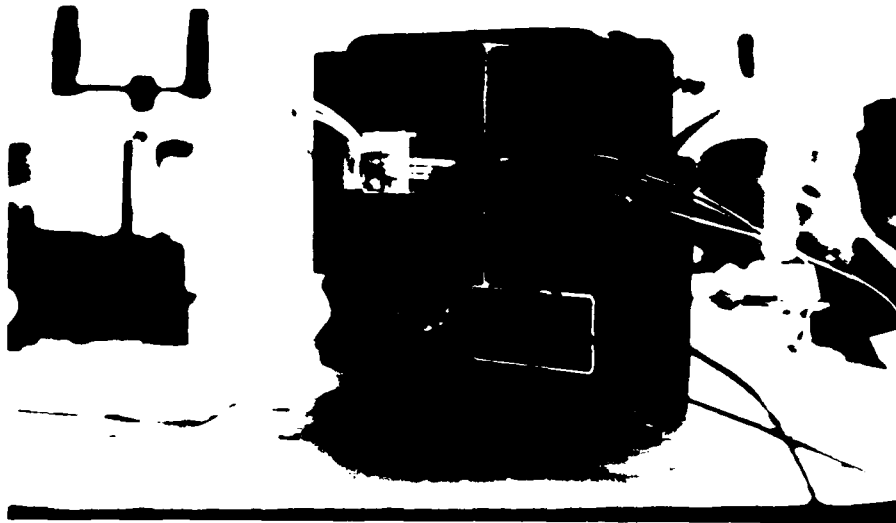


Figure 8 - Laser Diode Mounting System

The temperature controller reduced peak to peak temperature variations to  $>297\ \mu^{\circ}\text{C}$  over 20 minutes (See Appendix A). It is assumed that the temperature at the laser diode is one order of magnitude greater than the temperature measured at the thermister.

Acousto-Optic Modulator. An acousto-optic modulator shifts the frequency of light by light-sound interactions in an crystal medium. A sound wave traveling through solid consists of a sinusoidal perturbation of the density of the material. This change in density, in the first order, causes a proportional change in the index of refraction. In this situation the sound waves can be considered as a series of partially reflecting mirrors. In order for diffraction to occur in a given direction, all the points on a



mirror must contribute in phase to the diffraction in that direction. Also the diffraction from any two acoustic phase fronts must add up in the phase along the direction of the reflected beam. This condition is written as:

$$(20) \qquad 2\lambda_s \sin\theta = \lambda \qquad (15)$$

Where  $\lambda_s$  = The wavelength of the sound wave (rad/sec)  
 $\lambda$  = The wavelength of the optical wave (rad/sec)  
 $\theta$  = Bragg angle (rad)

At this angle  $\theta$ , the Bragg angle, the efficiency of the diffraction is at a maximum. The frequency shift of the optical beam is proportional to the frequency of the sound wave.

In the actual design of an acousto-optic modulator, light passes through an acousto-optic crystal. A PZT is attached to this crystal. The PZT is driven with a sine wave of the desired frequency shift causing the PZT to set up ultrasonic waves in the crystal, see Figure 9. In this laser diode research, the only function of the acousto-optic modulator is to isolate the diode from unwanted strong optical feedback off the linear interferometer. In the diffraction process the frequency shifted beam is bent away from the unshifted beam. A back reflection of the unshifted beam either passes straight through the crystal or is diffracted once again back down the original beam. This light has little effect since it is frequency shifted twice and lies outside the resonance frequency of the laser cavity, see Figure 10.

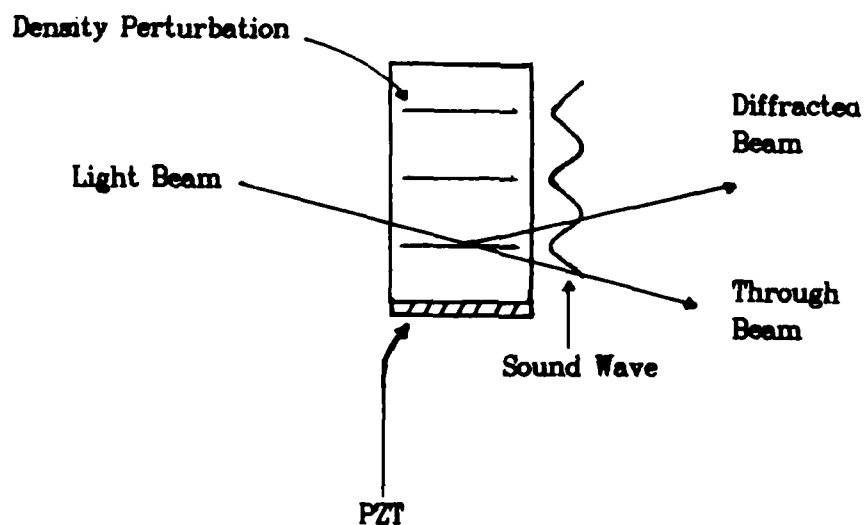


Figure 9 - Acousto-Optic Modulator Operation

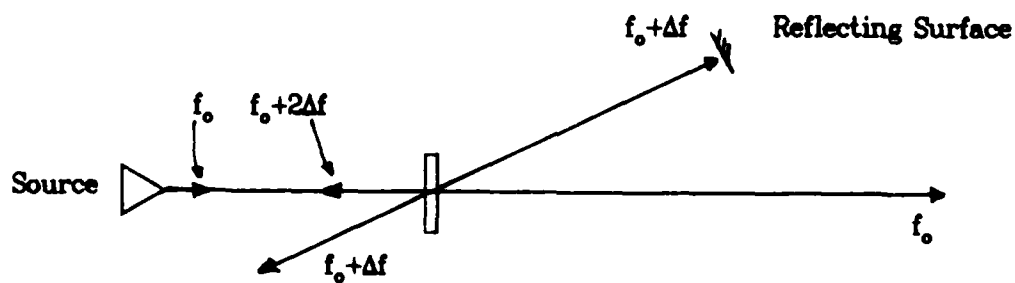


Figure 10 - A/O As an Isolator

Since the objective of this research is application of laser diodes to PRRLGa, it is appropriate and convenient to use A/Os as isolation devices as they will be directly applicable to a gyro configuration. In this research an acousto-optic modulator built by Coherent Associates is used. The A/O is designed for use at 40 MHz. The signal is generated by an HP 8649B signal generator and amplified by wideband RF amplifier built by RF Power Labs INC. The output of the signal generator is 40 MHz, .3v pp and this is amplified to an output power of 1.5 watts.

Scanning Confocal Fabry Perot Interferometer. Laser linewidth measurements can be made by a number of different methods. For laser diodes operating at 830nm two methods dominate, scanning Fabry Perot interferometer (SFPI) and optical self-heterodyne developed by Okoshi et al (21). In this research the SFPI is used to make linewidth measurements. To understand the information being displayed by the spectrum analyzer, it is important to understand how the device works.

The scanning Fabry Perot interferometer serves as a spectrum analyzer by scanning a bandpass filter across a given frequency range. The Fabry Perot cavity acts as an optical bandpass filter. On one or both of the mirrors is mounted a piezo electric transducer (PZT) servo which changes the distance between the mirrors, thus causing a change in the resonance condition. This is equivalent to scanning across a part of the frequency

spectrum. The next section discusses the Fabry Perot as an optical bandpass filter and reviews the attributes of confocal vs non-confocal cavities.

Fabry Perot Cavity. A Fabry Perot cavity consists of two reflecting surfaces arranged so that a wave incident to the cavity will reproduce itself after one round trip. The ability to transmit light through the cavity is a function of the resonance of the cavity. The cavity is in resonance when a wave travels one round trip ( $2L$ ) of the cavity and is in phase with the beam just entering the cavity. This match only occurs when the round trip is an integral multiple of the wavelength of the light,  $2L=n\lambda$  where  $n$  is an integer. Changing wavelength to frequency results in  $\nu=c/2L$ , which gives the resonant frequencies of the cavity. The distance between the frequencies is the free spectral range (FSR)  $C/2L$ .

When the cavity is in resonance, the maximum amount of light is transmitted through the cavity. This is a function of the boundary conditions at the mirror. The formula for transmission through an optical cavity is (20)

$$\frac{I_t}{I_i} = \frac{(1-R)^2}{(1-R)^2 + 4R \sin^2(\delta/2)} \quad (16)$$

Where  $R$  = Reflectivities of the mirrors  
 $\delta$  = Phase delay (rad)

Figure 11 shows equation 16 represented graphically for various values of  $R$ :

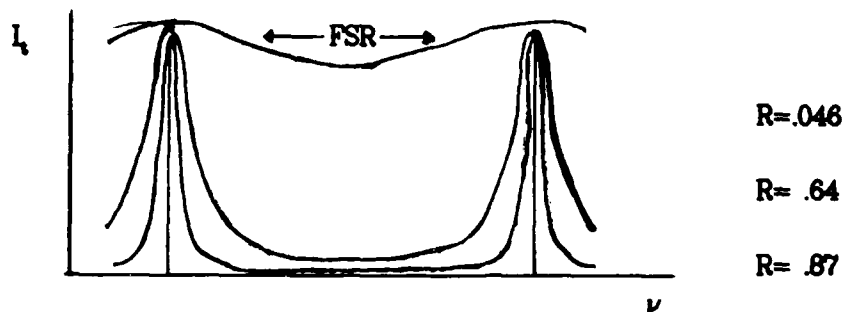


Figure 11 - Fabry Perot Transmission Curve

It is obvious that the Fabry Perot cavity will function as an optical bandpass filter, the resolution of which is determined by the reflectivity of the mirrors.

The analysis thus far is equally valid for confocal and non-confocal cavities. There is, however quite a difference in the transverse modal characteristics of these two types of cavities. For a confocal cavity the change in frequency  $\Delta\nu$  caused by a change in the transverse mode  $\Delta(m+n)$  is given by: (20)

$$\Delta\nu = \frac{1}{2} \left[ \Delta(m+n) \right] \frac{c}{2nl} \quad (17)$$

The transverse modes which result from changing  $m$  and  $n$  either coincide or lie halfway between longitudinal modes. Graphically the result is as follows:

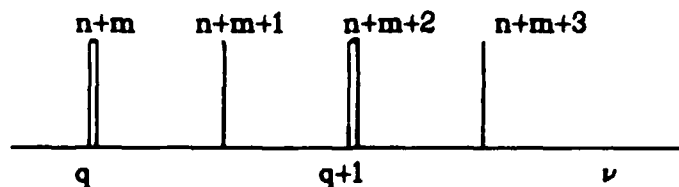


Figure 12 - Mode Configuration for Confocal Cavities

Notice for confocal cavities the FSR becomes  $C/4nl$ . For the non-confocal case:

$$\Delta\nu = c_0/2\pi n z_0 \quad (18)$$

Which is depicted as:

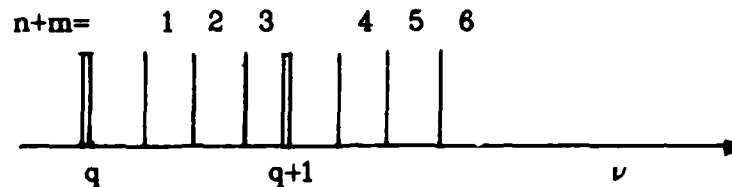


Figure 13 - Mode Configuration for Non-Confocal Cavities

This is a less desirable configuration in a scanning interferometer since modes higher than the fundamental transverse mode are easily generated. These modes cause confusion when trying to scale the trace. They may be eliminated by mode matching to the cavity but this increases the complexity of the device.

The advantages of using a confocal cavity over a parallel plate cavity are that mode matching is not required, it has high light gathering power and it has relative insensitivity to angular misadjustment. The drawbacks include intolerance to mirror separation distance, and fixed FSR. It makes most sense to use a confocal cavity if possible, especially in the case of laser diode spectral analysis. Since the diodes are extremely susceptible to the effects of optical feedback, optical components should be tilted in an attempt to eliminate this feedback. This may be done with a

confocal cavity without an appreciable loss of finesse and etendue. Losses are more severe with a parallel plate analyzer.

Scanning. As shown in the last section, a Fabry Perot cavity acts as an optical bandpass filter. This bandpass filter scans across the frequency spectrum as the distance between the mirrors is changed by the PZT. Scanning the bandpass filter across the line of interest results in a spectral analysis of the line, see Figure 14. As the filter scans across the line, the detector measures intensity vs time. Time is translated into frequency through the scanning function which drives the PZT. The scanning function typically used is a sawtooth, its amplitude is adjusted so a full FSR is viewed, see figure 15. If the cavity being used is confocal then, as explained in the last section, the two modes observed are a longitudinal and transverse mode. Since the FSR between those modes is given by the mirror separation, it may be used to scale the trace. Linewidth measurements are typically measured at the half intensity point (full width at half maximum).

Resolution. It is obvious from Figure 14 that the resolution of the SCFPI is limited by the instrumental bandwidth of the Fabry Perot cavity. The interferometer cannot resolve a feature which is narrower than the linewidth of the scanning cavity. The theoretical instrumental linewidth is given by (22):

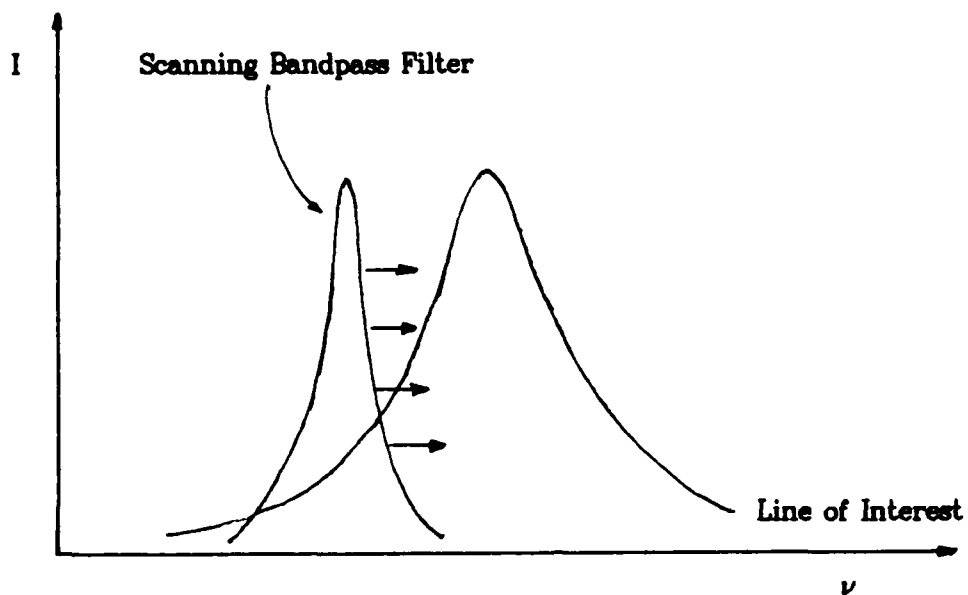


Figure 14 - Fabry Perot Scanning a Line of Interest

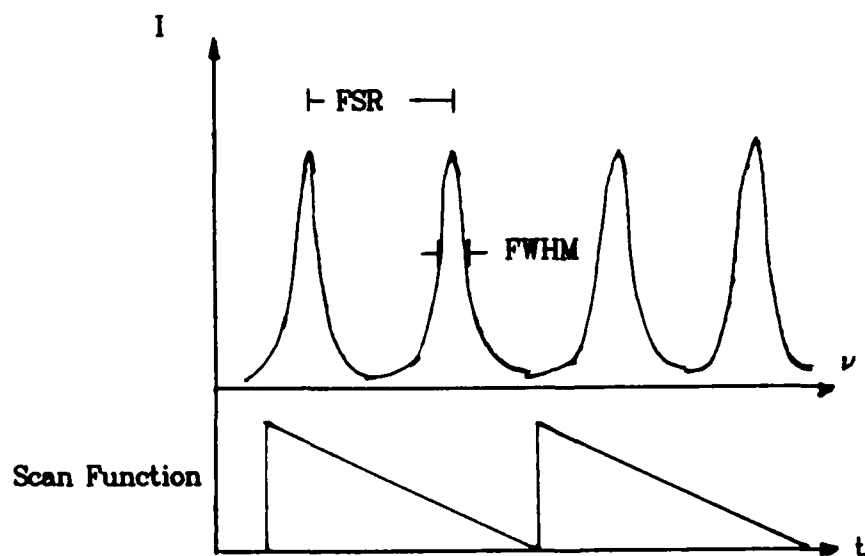


Figure 15 - Viewing a Free Spectral Range



$$\nu = \frac{c(1-R)}{2\pi d(R)^{1/2}} \quad (19)$$

Where     $c$  = Speed of light (m/s)  
            $R$  = Reflectivity of the mirrors  
            $d$  = Distance between the mirrors (m)

For Lorentzian lines the relationship between the observed linewidths

$\delta$ , true linewidth  $s$  and instrumental linewidth  $\nu$  is given by:

$$s \approx \nu + \Delta \quad (20)$$

Equations 19 and 20 can be used to determine the true linewidth of the laser source being examined.

Model 470 SFPI. The spectrum analyzer used in this research was a Spectra-Physics model 470 scanning confocal Fabry Perot interferometer. The mirrors available had a FSR of 2GHz and were coated for 830 nm. The driving unit is a Spectra-Physics model 476 which produces a sawtooth scanning voltage which can be adjusted in amplitude and frequency. A DC bias on the scanning voltage provides a centering capability and a blanking feature turns off the detector output during the sawtooth rise to eliminate "ghosts". The standard scanning rate for this research was 100 Hz.

#### Setup

The idea is to setup an external coupled cavity configuration which emulates the input optics to a passive ring laser gyro as much as possible.

The configuration shown in Figure 17 was used. The diode is mounted on a small piece of aluminum which allows access to the diodes terminals while giving the diode a flat side to mount on the cool side of a peltier cooler. The hot side of the cooler is fixed to a small aluminum block which acts as a heat sink to eliminate heat build up. The entire assembly is mounted on an NRC model 600A-2 optical mount. (See Figure 8) This assembly is then placed on an X-Y translator which gives the diode two different angular adjustments and two linear adjustments.

The next stage in the setup is the collimating assembly and feedback plate. These are also mounted on an X-Y translator. The two lenses are adjusted to give a slightly diverging beam with a diameter of 1mm at .5m. The glass feedback plate is mounted on a modified fiber optic coupler mount. This allows easy removal or addition of the glass plate without causing misalignment to the rest of the components. It also allows angular adjustment of the glass plate to control the amount of light fed back to the laser diode. The setup described so far can be viewed as the external coupled cavity semiconductor laser.

As mentioned in the equipment section, an acousto-optic modulator is used to isolate the laser from feedback off of the spectrum analyzer. It is set on a circular mount which can be adjusted to maximize intensity in the shifted beam. Finally, the spectral content of the beam is measured with the

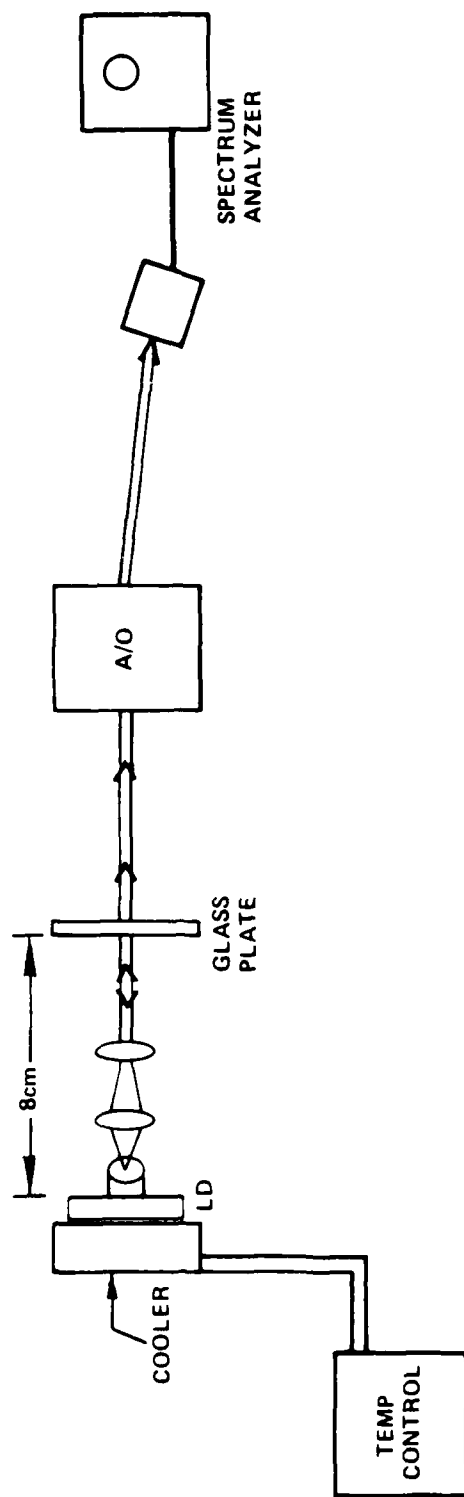


Figure 17 -- Experimental Setup

scanning Fabry Perot interferometer.

This setup is intended to emulate the input optics of a PRRLG, the only exception being the replacement of the beam guiding mirrors found in the gyro configuration. Instead, these are replaced with the spectrum analyzer. In this way the spectral content of the light, as it would be entering the ring cavity, can be measured.

#### IV. Results, Conclusions and Recommendations

##### Linewidth Measurements.

The spectral linewidth of a laser is typically given as the full width at half maximum (FWHM) of the trace. The trace obtained on the oscilloscope is a time vs intensity plot where time corresponds to frequency through the scanning function. The trace is calibrated by the FSR since this is known from the distance between the mirrors. In this case, a full free spectral range corresponds to 2 GHz which gives 50 MHz per small division at 500  $\mu$ s, 5 MHz at 50  $\mu$ s. To ensure linearity when increasing oscilloscope speed, a method other than simple trace measurement was used. The voltage to cross one FSR was measured and compared to the voltage to cross the linewidth. These results were within 5% of the results obtained by directly measuring the trace.

Since no spectrally narrow sources at 830nm were available, the resolution of the spectrum analyzer is not exactly known. The estimated finesse (which corresponds to instrument resolution) is between 100 and 300, giving a resolution between 7 and 20 MHz. Since it is unlikely that all three lasers will narrow to exactly the same value under feedback, this situation should indicate the resolution limit of the spectrum analyzer has been reached. In the case of two Lorentzian lines, the observed linewidth is the sum of the instrumental linewidth and the true linewidth. Therefore in

the described situation, the spectral linewidths being measured are much less than the resolution of the analyzer.

The first step was to measure the free running linewidths of the laser diodes. The Mitsubishi laser 83-15492 (Figure 17) shows a free running linewidth of 60 MHz. The Mitsubishi laser diode 83-15679, as shown in Figure 18, has a free running linewidth of 45 MHz. Finally the free running linewidth of the Hitachi diode is found to be 30 Mhz. (See Figure 19) Also quite obvious in Figure 19 is low frequency noise which is evident as a rapid jittering of the laser line.

Although the acousto-optic modulator does a good job of removing the strong feedback from the spectrum analyzer, there is still a small amount of weak feedback remaining. This is evidenced by changing the diode current which is equivalent to changing diode frequency. As the laser line runs across the screen, a slight narrowing and widening of the line is evident. This results from the weak feedback narrowing the linewidth as a function of the phase of the feedback. As a result, the actual free running linewidths of the lasers may be wider than measured.

Introducing feedback to the lasers results in spectral narrowing. Besides the obvious narrowing, there is an increase in intensity at the central frequency. This occurs as power, which was previously contained in frequency noise, moves to the resonant frequency. Figures 20 and 21 show the dramatic results obtained with the Mitsubishi laser diodes. Figure 22

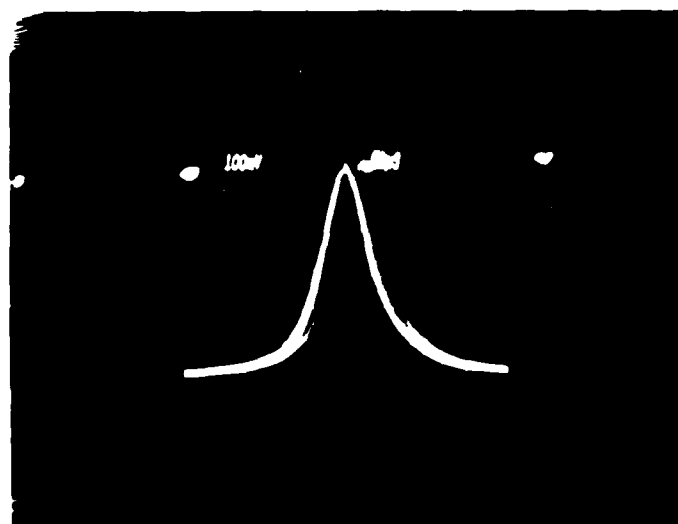


Figure 17 - Laser Diode 83-15492 Free Running Linewidth

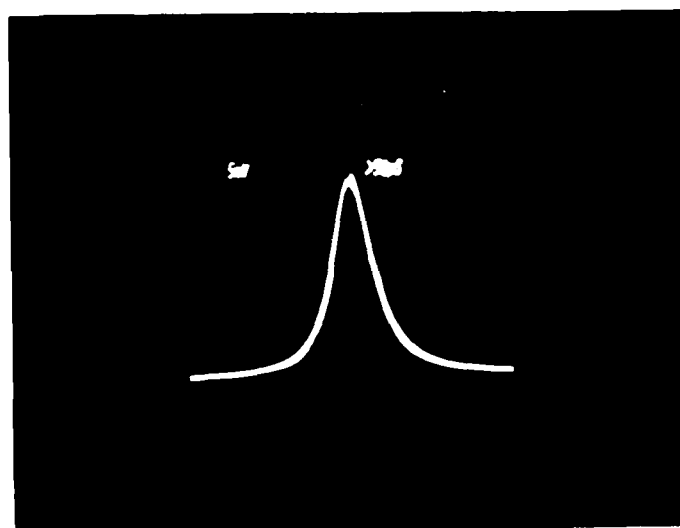


Figure 18 - Laser Diode 83-15679 Free Running Linewidth

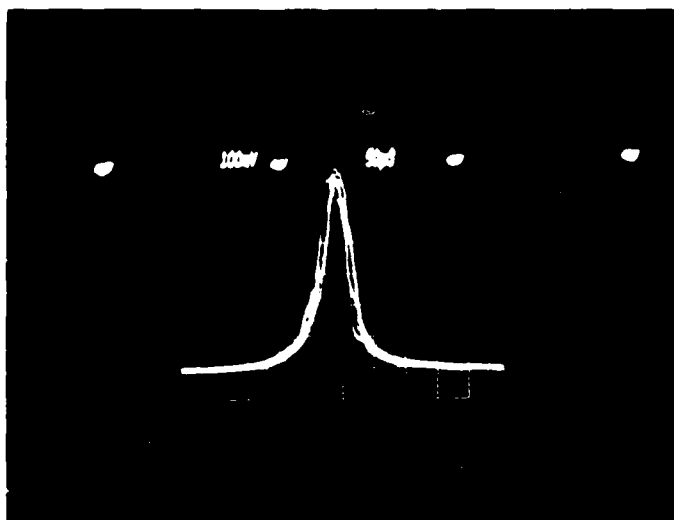


Figure 19 - Hitachi Laser Diode Free Running Linewidth



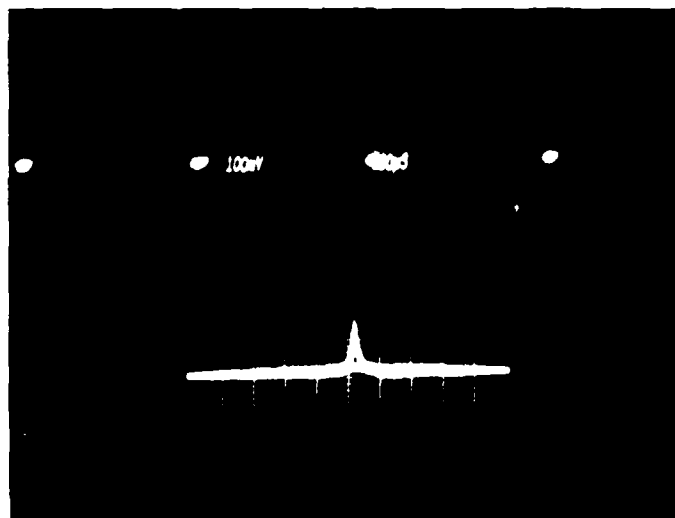


Figure 20 - Mitsubishi Laser Diode with No Feedback

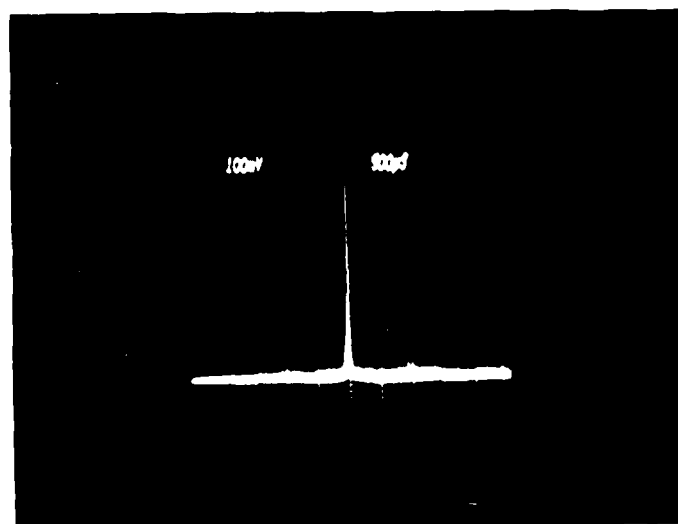


Figure 21 - Mitsubishi Laser Diode under Feedback

graphically depicts the process shown in Figures 20 and 21 by superimposing the two traces on each other. As shown in Figures 23, 24 and 25, a maximum narrowing of 13 MHz resulted for all three laser diodes.

Mode Behavior. The amount of narrowing obtainable by optical feedback is limited by mode behavior under feedback. Theory predicts that as the strength of feedback increases, the laser will eventually become multimode. This was verified experimentally. Figure 26 shows the Hitachi laser as the strength of feedback is strong enough to generate two small side peaks. In this condition the laser may be adjusted back to a single mode condition simply by adjustment of the injection current. As feedback strength is increased, the side peaks increase. As feedback strength increases still further, eventually a multimode condition persists as shown in Figure 27. Finally, very strong feedback results in a degenerate condition in which the modes rebroaden, see Figure 28.

The modal characteristics of both types of semiconductor lasers match very well the behavior predicted by theory. Since the purpose of this research is to obtain a single mode narrow linewidth laser, the feedback is increased until just before a multimode condition. This results in maximum narrowing and still maintains the single mode behavior.

Operation. The external coupled cavity semiconductor laser (using either brand of laser diode) was found, by simple observation, to operate in

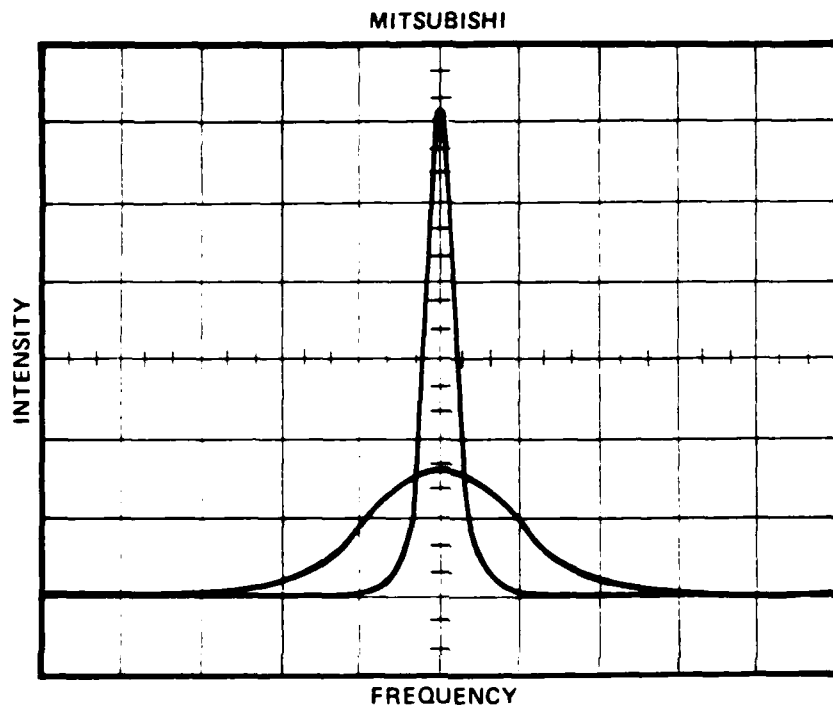


Figure 22 - Mitsubishi Laser Diode: No Feedback vs Feedback

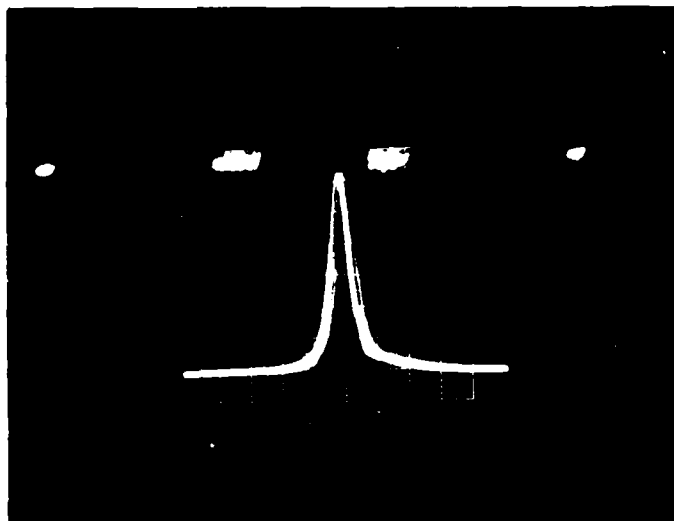


Figure 23 - Spectrally Narrowed Laser Diode 83-15492

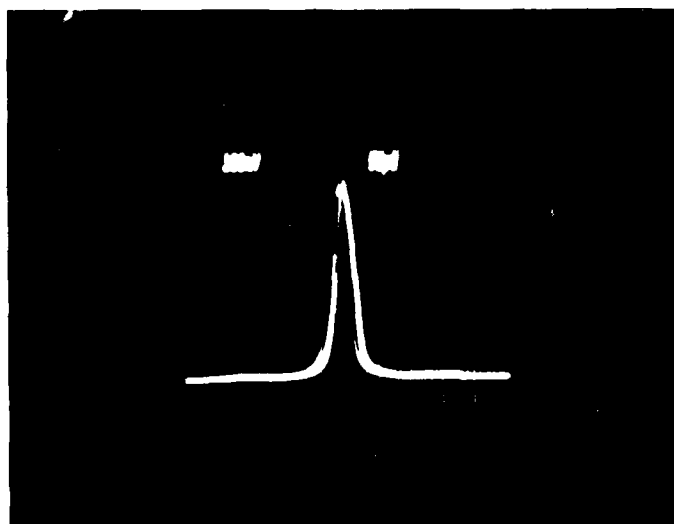


Figure 24 - Spectrally Narrowed Laser Diode 83-15679

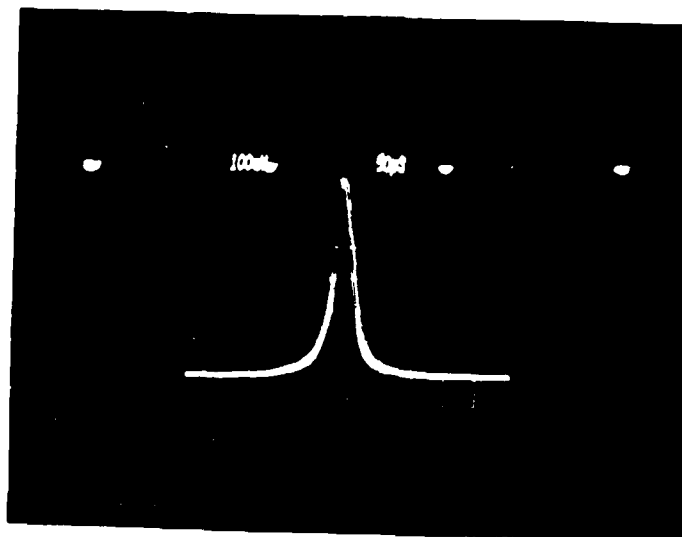


Figure 25 - Spectrally Narrowed Hitachi Laser Diode

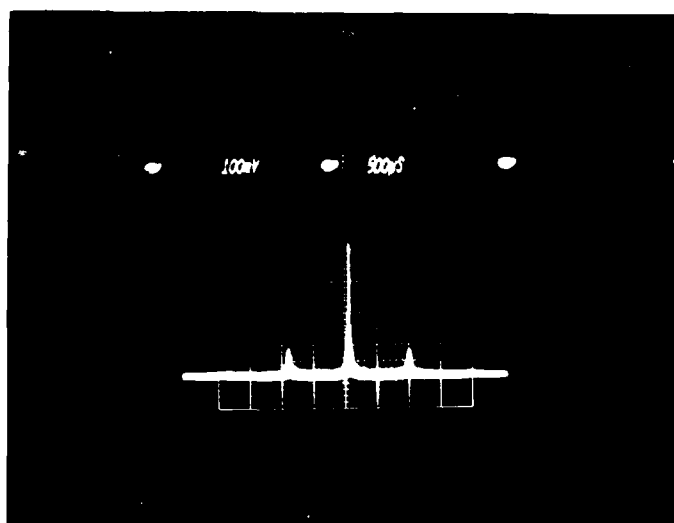


Figure 28 - Three Mode Operation due to Optical Feedback

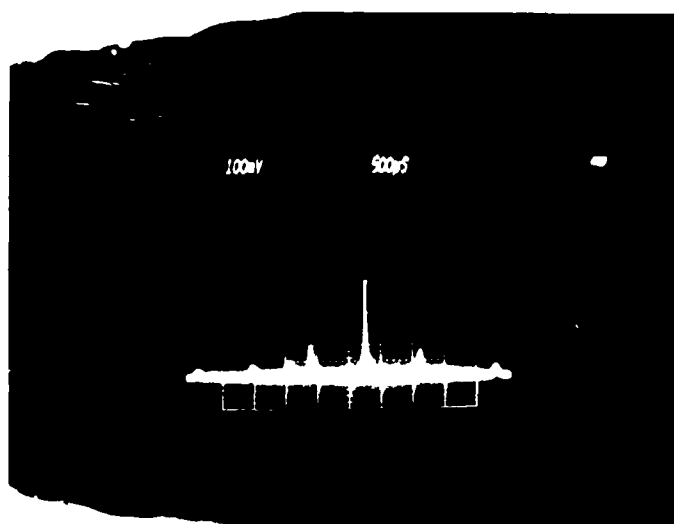


Figure 27 - Multimode Operation due to Optical Feedback

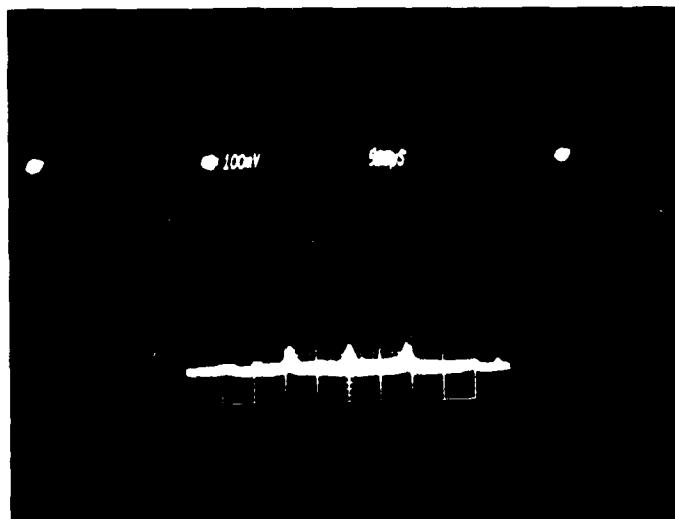


Figure 28 - Spectrally Broadened Multimode Condition due to Optical Feedback

a single narrow mode for up to 20 minutes. At this point, thermally induced variations in the external cavity caused a mode jump. The narrow spectral linewidth of the laser proves that frequency noise has been reduced, making this laser more suitable to lock to a narrow linewidth cavity.

#### Conclusions and Recommendations for Further Research

To realize high sensitivity semiconductor laser based PRRLGs, it is necessary to narrow the spectral linewidth of semiconductor lasers. This research has applied the method of optical feedback to three semiconductor lasers and has shown such spectral "preconditioning" is a simple, effective way of obtaining narrow spectral linewidth semiconductor lasers for application to highly sensitive PRRLGs. The laser diodes were modified, tested and proven to work within the constraints of the simulated PRRLG configuration. The acousto-optic modulator proved to be an adequate isolator for this application. When implemented in the actual gyro configuration, the spectrum analyzer will be replaced with a ring cavity which, because of the angle of the input mirror, will not generate as much feedback to the diode. Therefore the external coupled cavity semiconductor laser can be expected to work under these more relaxed constraints.

The constructed external coupled cavity semiconductor laser will be suitable to investigate locking semiconductor lasers to high finesse ring cavities. The Frank J. Seiler Research Laboratory currently possesses a



highly stable, high finesse (estimated theoretical finesse of 10,000) ring cavity coated for 830 nm which may be used for this research. To lock the semiconductor laser to the cavity and maximize the S/N at the detector, it will be necessary to employ very wideband electronic controllers. Wideband control techniques for laser frequency locking to a cavity have been developed for dye laser frequency stabilization (23). The results obtained from this research may be used to develop a highly sensitive semiconductor laser based PRRLG. The use of fiber optic input loops would further decrease the size of the gyro. The ultimate goal would be highly sensitive, compact, rugged PRRLGs for precision rotation sensing applications.

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## Appendix A - Electronic Circuits

Appendix A details the buffer circuit used to improve the output of the dc power supply and also gives the circuit form of the PID controller used to temperature stabilize the laser diodes. The power supply buffer circuit is given as follows:

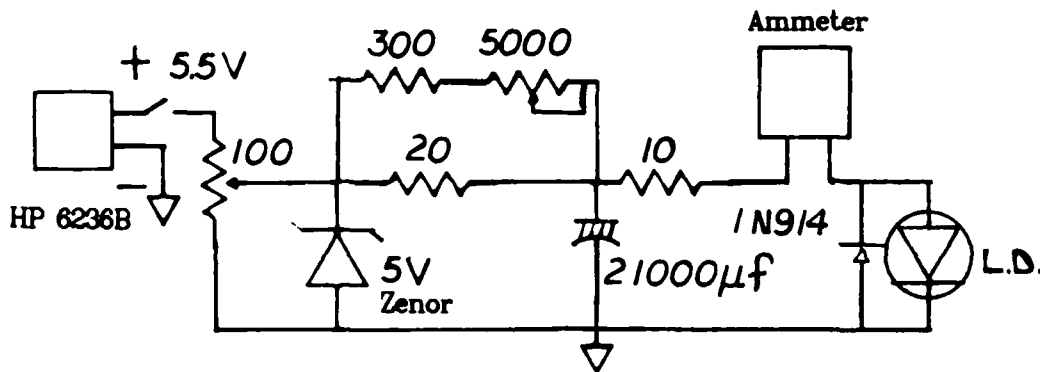
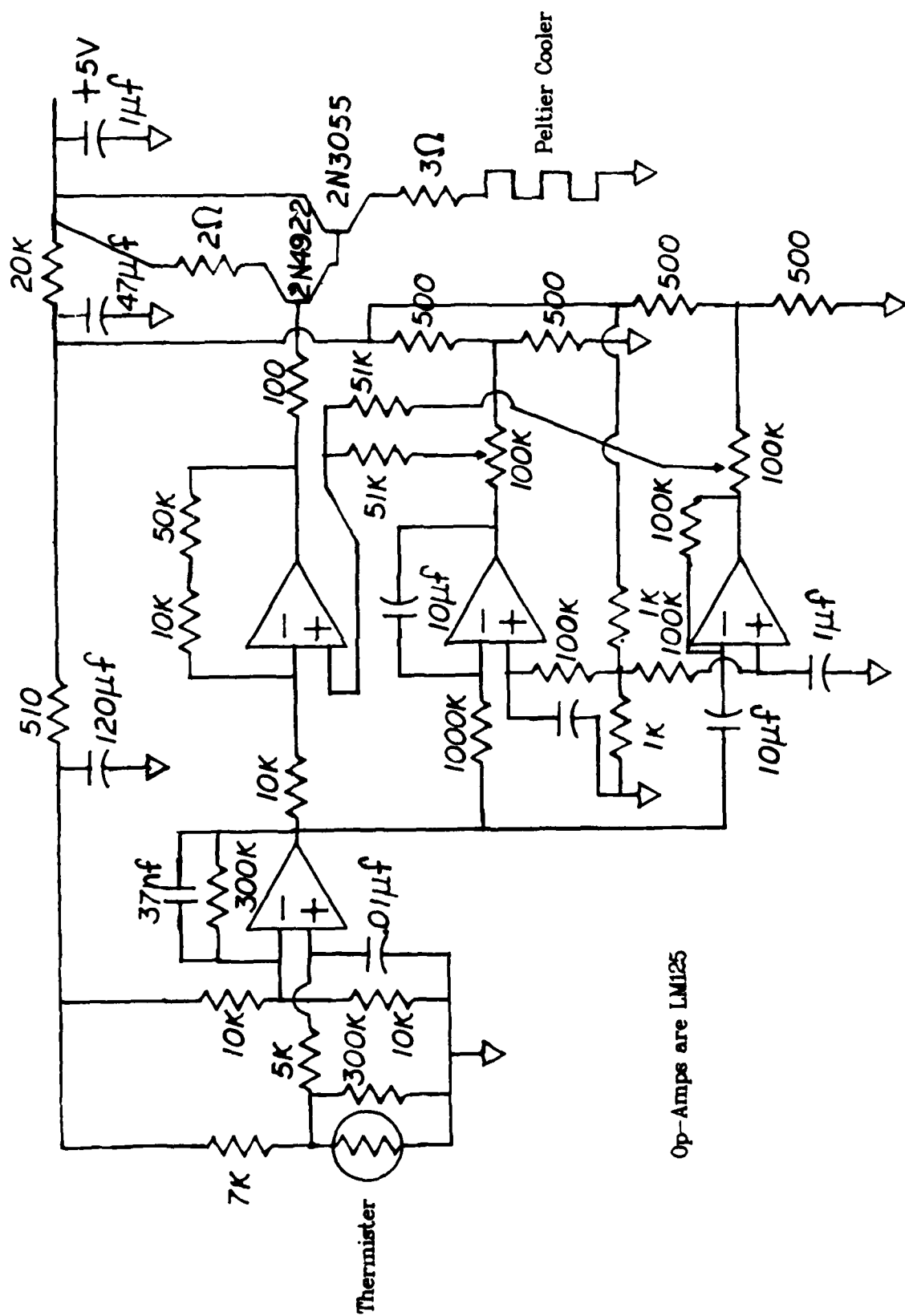


Figure 29 - Power Supply Buffer Circuit

The switch energizes the circuit after the main power supply has been turned on. The 100 ohms variable resistor is a coarse current adjustment and the 5k ohm variable resistor is fine tuning.

The following is the circuit diagram of the PID temperature controller used to temperature stabilize the laser diodes: (From discussions with Dr. J.L. Hall, JILA, National Bureau of Standards, Boulder Co.)



The high sensitivity thermister is built by YSI corporation, model 44634 and the cooler is a .71" x .71" peltier cooler built by Marlow Industries. All bridge resistors are 1% metal film to minimize temperature induced resistance changes in the reference resistors.

The controller uses a resistor bridge to compare the thermister resistance against a fixed setpoint resistance. The error signal is generated by a differencing op-amp and the run through the PID channels. Finally the error signal is current boosted and feedback to the peltier cooler.

The temperature of the laser diode is monitored by monitoring the signal out of the differencing op-amp. Sensitivity at this point is 3.362 V/°C. A Texas Instruments strip chart recorder is attached to the test point to show peak to peak temperature variations.

## Vita

The author Capt. Daniel Stech was born in Harvey Illinois. He attended Hillcrest high school and upon graduation accepted an appointment to the U.S Air Force Academy. He graduated in 1981 and remained at the Academy for 6 months working the in chemistry section of the Frank J. Seiler Research Laboratory (FJSRL). In 1982 he completed the aircraft maintenance officer course at Chanute AFB and was assigned to the 87 Fighter Interceptor Squadron at K.I. Sawyer AFB Michigan. In 1985 he attended AFTT and studied in the area of guidance and control. He is presently assigned to the laser gyroscope section of the FJSRL at the Air Force Academy.

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Reduced cost, greater reliability, and compatibility with integrated optics are some of the advantages gained by incorporating semiconductor lasers into the design of passive resonant ring laser gyroscopes (PRRLG). Unfortunately, the large spectral linewidth typical of semiconductor lasers greatly limits the sensitivity of such a configuration. This research details the modification of a laser diode to obtain a stable, single mode, narrow spectral output. Optical feedback was investigated to obtain spectral narrowing of the laser diode. An optical feedback configuration compatible with the integrated optics to a PRRLG was designed. Spectral narrowing and modal dynamics of the external coupled cavity laser were measured. By temperature stabilization and optical feedback a free running linewidth of 60 MHz was reduced to below 13 MHz and was maintained in a single mode for 20 minutes or more. *Key words: laser, optical feedback, PRRLG*

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